# Improvement in Reliability, Availability and Maintainability (RAM) using Reliability Centred Maintenance (RCM) in Liquefied Natural Gas (LNG) loading arms.

Erik Vandenberg and Gopinath Chattopadhyay

***Abstract*—** New facilities are opportunity rich environments in terms of the ability to make changes which may bring about significant improvements to reliability, availability and maintainability (RAM). High RAM and lowest possible life-cycle costs (LCC) are goals which any effective maintenance program should work to achieve. Pre-emptive interventions, through Preventative Maintenance (PM), should balance the cost of maintenance with the elimination of degradation and failure mechanisms. PM is performed to avoid the burden and cost of failures in operation, which would require Corrective Maintenance (CM) which tends to be more expensive and less safe to carry out. PM activities themselves, can introduce additional damage and failure mechanisms, plus they also cost money to perform. Determining the optimum PM frequency and type of PM, requires these cost/benefit type factors to be analysed and optimized based on risk. Excessive PM activities will introduce additional costs and opportunity for damage due to interventions made by the maintainers, which could lead to significantly increased life-cycle costs, reduced reliability, and availability. Insufficient PM could allow equipment to wear out, leading to increased failures and reduced overall reliability of the system or facility to which they belong.

To optimise the maintenance program, analysis of failure modes, their effects, and criticality of these effects should be carried out, in relation to what the owner of the system or equipment wants it to do, then recommendations for maintenance, inspection and testing programs be made using Reliability Centred Maintenance (RCM) decision logic methods, to align the maintenance strategies with how the equipment fails, how predictable the failure is and what overall impact the failure has to safety, the environment, and production. The application of RCM to new assets, once they have been operating for some time is of value, largely because new knowledge and experience with the actual built asset, provides insight that was not available at FEED or detailed design phase. From actual reliability data, through to a real understanding of the actual operating environment. This new knowledge used in carrying out an failure, modes, effects and criticality analysis (FMECA) study, with subsequent application of RCM decision logic, can bring about significant improvements to an existing maintenance strategy, or alternately are excellent ways to formulate one if there is not already one in place.

***Keywords*—**Failure Modes, Events and Criticality Analysis, FMECA, RCM, Reliability Centred Maintenance, Maintenance Optimization, Maintenance Strategy.

## I. INTRODUCTION

THE Ichthys onshore LNG processing facility in Darwin, Australia, includes marine loading arms (MLA's) at the end of both jetties, one set for the LNG jetty, and on the other jetty, another for butane/propane (LPG), and condensate. The criticality and readiness of these is deemed high to business operations in meeting our contract commitments to customers. In the event of a failure of one LNG liquid/hybrid arm this will reduce loading from 12,000 m3 to 10,000 m3 per hour. The failure of further arms (leaving one vapor arm and one liquid arm operations) will further reduce loading to 5,000 m3 per hour.

Fig. 1 Loading arms connected to an LNG tanker

It is essential all maintenance is executed in the non-operational windows between LNG loading to maximize loading system availability, the frequency of LNG ships to the terminal is around every 72 hours. Typical turnaround time for loading from first line ashore to last line off is 29 hours including tidal restriction, with average fill time of 15 hours of an LNG carrier of 155,000 m3.

It has been noted that there are some opportunities to make improvements to the maintenance build, using RCM to provide the opportunity to optimize, with operational experience with respect to the arms and associated equipment. The OEM (Original Equipment Manufacturer) generic recommended

Erik Vandenberg is with INPEX Australia, and is a Student of Federation University +61 413 576 600; erik.vandenberg@inpex.com.au.

G Chattopadhyay is with Federation University, Northways Road, Churchill, PO Box 3191, Gippsland Mail Centre, Vic 3841, Ph: +61351228629 and +61402467737, Email: g.chattopadhyay@federation.edu.au

FEED, an excessive and conservative approach at best, not considering the specific usage parameters and environmental conditions unique to the installed location, with hard-time based complete overhauls of the components and the entire arms, which would necessitate removal of the arms every 5 years using a floating barge-crane.

The RCM [1], [2], [3], [4], [5], [6], [7] methodology, originally developed for the aviation industry [8] has been used effectively in conjunction with FMECA, [9], [10], [11] a widely used tool for reliability analysis [12] which can be used to help engineers to define suitable maintenance strategies [13]. RCM has been used with FMECA and/or Fault Tree Analysis (FTA) [14], [15], [16] methods in the military, nuclear, oil and gas, and chemical processing industries, to reduce maintenance burden and support costs whilst ensuring continued preservation of a required state of readiness or operability. The "optimize the use of resources allocated for maintenance and to ensure the availability of the plant" [17]

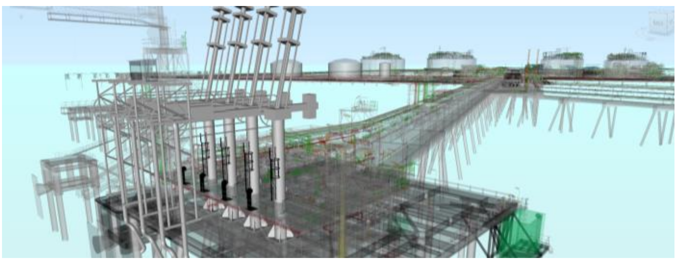

Fig. 2 Three-dimensional model view of the LNG loading arms

FTA, a method of focusing on each failure and determining possible causes of that event [18] can be used for determining failure mechanisms, these can then be considered in an FMECA to determine the effects and criticality ranking of each failure, known as the RPN (risk priority number), which is mathematically expressed by **RPN =**(OR)(SR)(DR), where OR = occurrence ranking, SR = severity ranking, DR = detection ranking [18]. The RPN, or criticality ranking is a list used to rank the failure modes, from most to least critical. This can be conducted using quantitative, or qualitative (subjective) analysis, depending on the availability of reliable failure data, if no such data exists, the study can be conducted based on experience of team members [19], then once operational data is collected the study can be revised using this data. In summary, the FMECA process, an approach for the analysis of each potential failure mode of a system, the effects of those failure modes, and classification of each effect according to its severity is a routine approach that improves communication and understanding of systems amongst team members [20] and forms the building blocks for the RCM process.

For a FMECA to be successful, participants must have a good understanding and knowledge of the specific system functions, potential failures and failure modes, therefore it is of great benefit to ensure the right discipline engineers, operators, and maintainers are in the room. A side benefit is that this also serves to get 'buy-in' to the maintenance program from production personnel [21]. Some examples can be seen in figure 4 of different levels of analysis and their related functions, functional failures, and failure modes.

Once all potential functional failures have a calculated risk priority number, the items with the highest scores should be evaluated first using the RCM decision logic, to determine the optimal maintenance strategy. The outputs should maximise the availability of a system and ensure safe (non-hazardous) and economical operation and support [4]. The process, driven first by safety and then by economics [22], ensures the most economically optimal preventive maintenance strategy shall be selected only to the point where intolerable safety risks are not introduced. An RCM decision logic tree should be used to formulate recommendations for suitable maintenance strategies.

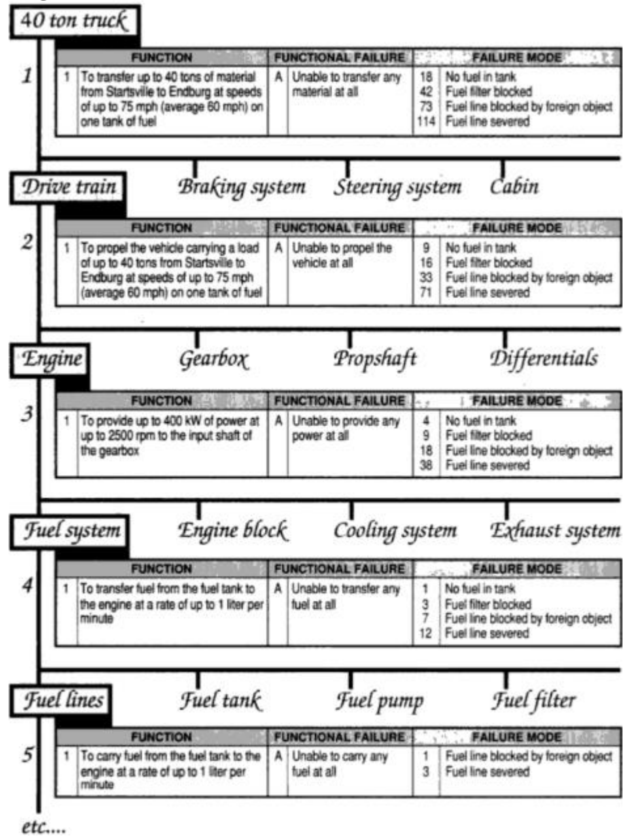


Fig.4 Functions and failures at different levels [21]

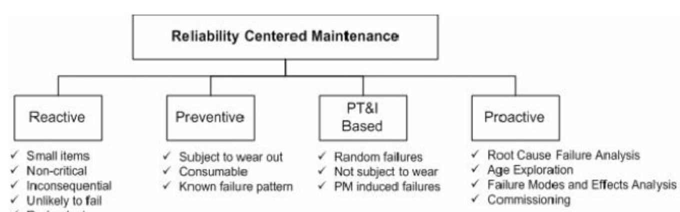


Fig.5 Components of an RCM Program [23]

Further benefits of an RCM program are improved morale, teamwork and individual motivation, with the success of the wider organisation positively impacted by the cooperation and improved communication that is fostered by an RCM program across the different departments and disciplines, and the gains in knowledge and understanding of plant and equipment enhancing the individual team members confidence and sense of ownership [24]. For companies in the process industries, particularly operators of major hazard facilities, where 'high-reliability' is imperative, or 'high reliability organizations' (HRO's), RCM serves to reinforce focus on preoccupation with failure, analysis of the root cause of failures, and subsequent revision of procedures [25] to reinforce the culture of a learning organisation. This process also supports the principle of continuous improvement and respect for people, two of the key pillars from the 'Toyota way' [26], aligned to the premise that 'the wise mend their ways' a philosophy adopted by Taiichi Ohno, the visionary who helped revolutionize the Toyota motor company and the automotive manufacturing industry. Involving maintenance personnel in the RCM process gives them an insight into the structured FMECA thinking and importance of accurate failure data recording, although there is no certainty that reporting will improve, the ownership of the process by maintenance personnel should provide motivation to improve reporting quality [27]

When a maintenance strategy is developed in the front end engineering design phase, often OEM vendor recommendations are adapted, without having the experience with the built asset to base the recommendations on. The vendor does not know or understand the specific details about how you will use the equipment [28] or the specific operating environment, including environmental conditions, temperature, vibration, UV exposure, presence of airborne contaminants, carbon, chloride, humidity, etc. It is also worth noting that an OEM would naturally be bias toward recommendations that yield a positive commercial benefit for them, such as aftersales support, parts sales and avoidance of warranty claims, thus by nature tend to be overconservative. OEM recommendations, usually simple time based policies, assuming the theory of a known and measurable failure distribution, or prediction of one, following some sort of probability distribution curve over time [29], [30].

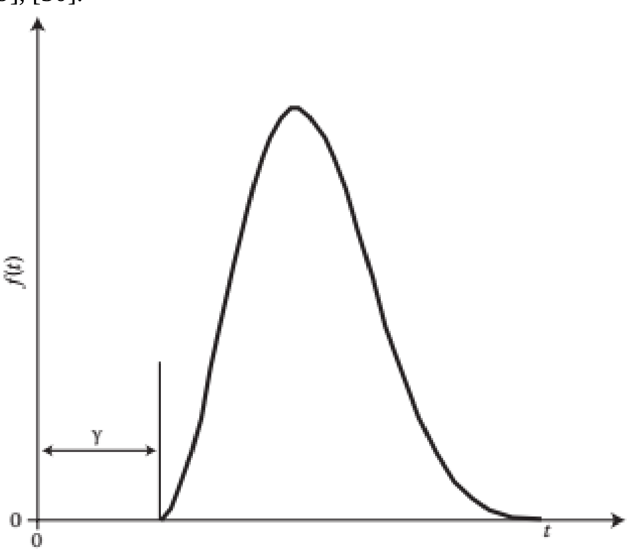


Fig.7 A Weibull failure distribution [31]

Despite the widespread belief that components or equipment follow this rule set when failing, also exhibiting 'bathtub-curve' characteristics, where the 'burn-in' and 'wear-out' periods are the times where most failures occur, there is new evidence that this is more often not the case [6], new knowledge which lends itself to pointing optimal maintenance strategies to predictive, condition-based methods wherever possible, to increase total availability and maximize MTBF. It is essential to pass this knowledge on to any engineers who may be opposed to the RCM approach due to the old beliefs which have now been updated with thanks to United Airlines and the databases of failure data they have collected to develop new age-reliability patterns [32], the results of which are summarised in figure 9.

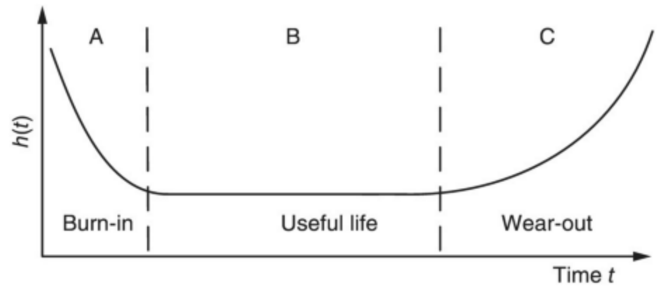


Fig.8 Typical bathtub curve [29]

The results of the data collection efforts by United Airlines were a surprise to most people, as they are still today, when people are looking at the results for the first time, the significance and importance of these results to the maintenance engineer cannot be overstated [32]. Important to note, is that only around 4% of the components followed the traditional bathtub curve as can be seen on curve A in the illustration. With only 11% showing signs of traditional age-based failure patterns, this means that the 89% remaining would not benefit from a limit on operating age, or hard-time-based maintenance strategies. Simply put, this means that a preventive time-based maintenance system based on this bathtub curve concept for all equipment means waste, retiring components early and introducing much maintenance that is not needed, which in itself can increase the failure rate of equipment in the immediate future [33].

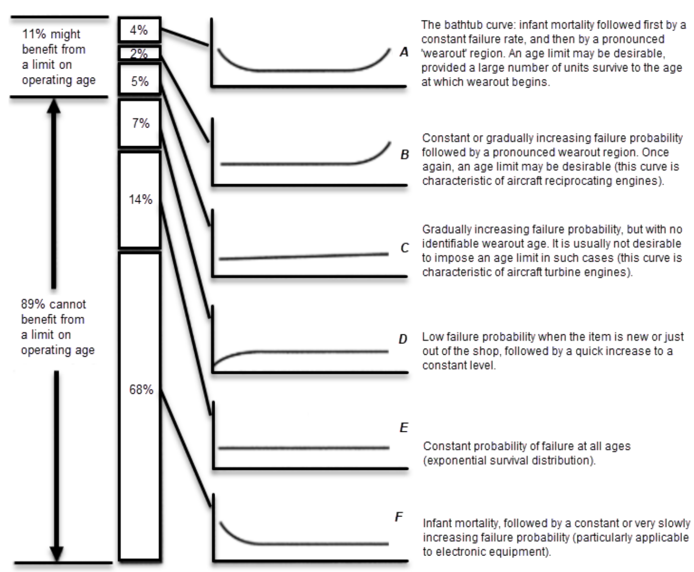


Fig.9 Age-reliability patterns from United Airlines data [6]

It is proposed that INPEX adopt an RCM approach to revising current maintenance strategies, using the marine loading arms as the first system to develop a blueprint for a process that can be routinely applied to all maintenance strategies over the life-cycle of the facilities. There are several variations of RCM decision logic that can be used to develop optimized maintenance strategies using the outputs from the FMECA, some of which are relatively simple and easy to understand and apply, others being more complex and not as clear for the uninitiated engineer. The key point of all the logic trees is to ask questions that guide the engineer/s using them, to formulate the optimal maintenance strategy. For example, the tree in figure 10, from the United States Department of Defence [4], prompts the lubrication or servicing tasks to prevent failures, inspection or functional testing to detect degradation, then restoration/repair or discard task as appropriate, leading to the most effective task, or combination of tasks. If none of the potential maintenance tasks are applicable and effective, the tree prompts the mandatory redesign of a system that can fail to a hazardous state, which makes logical sense. For operators of a major hazard facility, the inability to detect or prevent an impending hazardous failure is unacceptable.

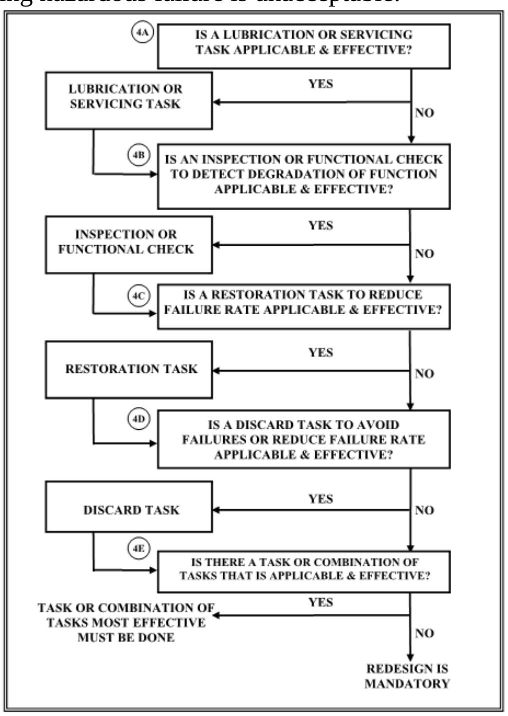


Fig.1 US Military RCM decision logic for evident failures with hazardous effects [4]

The objective is to use a decision logic tree that is easy to follow and understand so that it can be successfully applied, routinely and repeatably by several different engineers who may not always specialize in maintenance and reliability. The decision logic should ensure the most optimal maintenance strategy recommendations, where PdM and CBM are applied wherever applicable and effective. A review has been conducted of the various decision logic trees, including mapping of the decision logic employed in the reliability software package in use by the company, to find a suitable tree that can be applied for the INPEX RCM workshops moving forward.

## II. METHODOLOGY

A thorough review is to be conducted of MLA maintenance using Reliability Centred Maintenance (RCM) and Failure Modes, Effects & Criticality Analysis (FMECA) methodologies described in the referenced literature. A series of workshops and analysis to be conducted, that develop recommendations to be proposed using the INPEX management of change system, and updates to documentation and maintenance data as required. The first workshop, a day long FMECA session, was held at the INPEX LNG processing facility in Darwin, NT, Australia, with participants from multiple departments and disciplines, including Engineering, Production and Maintenance. An RCM analysis workshop was then carried out to develop recommendations to update the maintenance strategies based on optimised strategy formulated using RCM logic similar to that used by NASA, which helps easily identify appropriate strategies, such as predictive type test and inspection strategies to detect impending failure modes before they lead to a functional failure, or to detect hidden failures of on-demand type items such as safety instruments, before the hidden failure may be the cause of an inoperable safety function, preventive maintenance tasks, which attempt to restore condition of a component or system on a time-based frequency back to its design performance levels, system redesign actions where no other effective approach can be found, and finally run-to-fail strategy where this is found to be sensible. [9] It is necessary to understand the P-F interval when formulating recommendations for maintenance strategies, the curve below from RCMII [2] shows how for the functional failure of a bearing seizure, there are multiple potential detection points before the actual functional failure occurs. The key points to note are if the impending functional failure can be detected before a components function is degraded to the point that it fails to perform its intended function, if so, is this practical/economical to monitor and is there the ability to carry out corrective or mitigative actions in time to avoid any production losses.

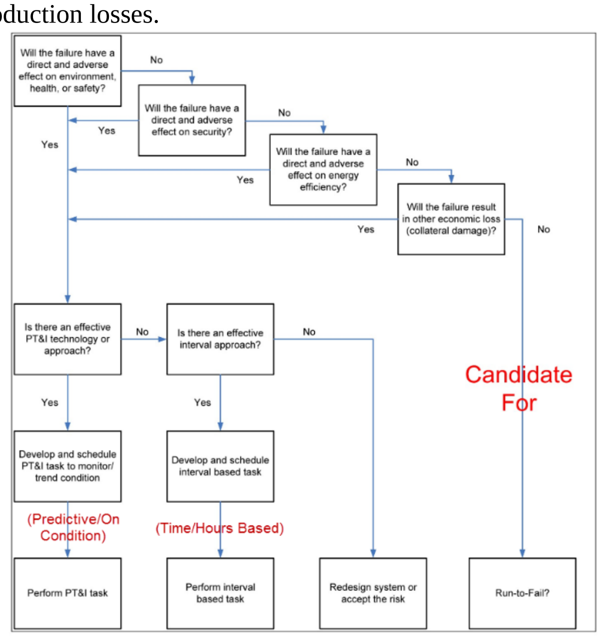


Fig.2 NASA RCM Decision Logic Tree [23]

If this is the case, then the P-F interval can serve us, and we can propose an on-condition task. Where the P-F interval does not allow enough time to plan and perform a corrective or mitigative action that would be required to avoid the production impact, we may need to look to another type of strategy.

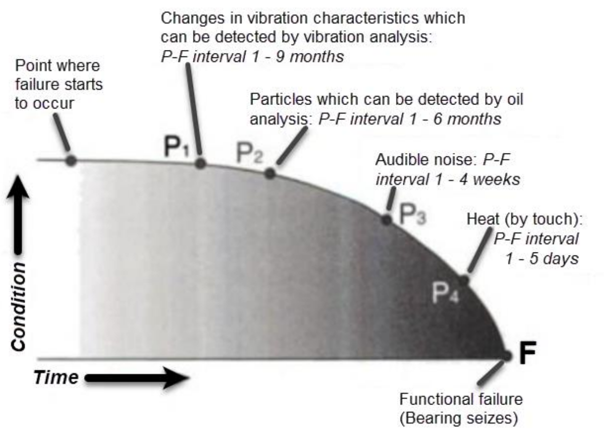


Fig.3 P-F Interval showing multiple potential points of detection before functional failure [21]

The RCM decision logic tree which we used (figure 14) asks simple questions to determine the optimal strategy. Using the decision logic tree, the engineer evaluates each option for its technical feasibility and its impact on safety, environment, production, and cost. The option/s that meet the organisations safety and environmental requirements, creating the least impact on operations and cost [34] is selected and recommended for implementation in the updated maintenance strategy. If there is a condition that can indicate an early warning of failure, with a consistent P-F interval to allow a corrective response that will not affect production, an on-condition, predictive maintenance (PdM) type task may be appropriate. The objective is to use NDT methods to detect variables that predict impending failures before they happen, to allow the preventive maintenance to be scheduled [35] to maximize availability. For example, a bearing that will give adequate warning before it fails that could be picked up by vibration monitoring [36] could likely be a candidate for an on-condition strategy. Providing the random nature of timing for signs of impending failure doesn't disrupt production, for example in an N+1 arrangement, the simplest form of standby system, where one component is operating and a spare one is on standby [37], on-condition could be the right answer. Where the answer to this first question is no, because of a lack of redundancy leading to a production impact, we then ask if the time before failure of the item is predictable and consistent, if so, then it may be more optimal to implement time-based repair/restoration or complete replacement tasks. For example, the overhaul of a non-spared machine like an industrial gas turbine or compressor, may best be done on a time-based interval if the failure of such an equipment item may lead to an inefficient unplanned rectification activity, causing avoidable additional down-time with significant losses due to deferred production, as opposed to if this can be done in a planned manner, giving the organisation the opportunity to properly plan and execute the activity in the shortest time period at a suitable time. For hidden failures, for example a faulty gas or infra-red fire detector, function tests at fixed intervals may be appropriate, and if the failure mode remains untreated then further analysis will be required, with potential for a design change to be suggested.

Interestingly, when we apply the QRCM (Quantitative RCM) decision algorithm, another process using reliability techniques to optimise maintenance strategies [38], to some of the functional failures assessed in the INPEX RCM workshop, this leads to the same outcomes. For example, application of the QRCM logic to the large structural bearings, leads to effective lubrication and condition monitoring. When we apply the QRCM logic, the fact that there is a measurable degradation parameter leads us to a condition monitoring task, a logical recommendation.

The steps of the FMECA process, as part of the RCM strategy shown below in figure 18, were used to identify failure effects and severities, considering the current detection method based on design and procedures, to rank each failure mode in terms of criticality for treatment, to allow prioritisation of resources to focus on the most critical items first. It may also be used to identify items of least criticality with the potential to decrease maintenance burden which may have previously been set to over conservative strategies, the revised RPN (Risk Priority Number) can be calculated based on theoretical changes to the maintenance strategy to allow us to then assess the tolerability of this residual criticality ranking.

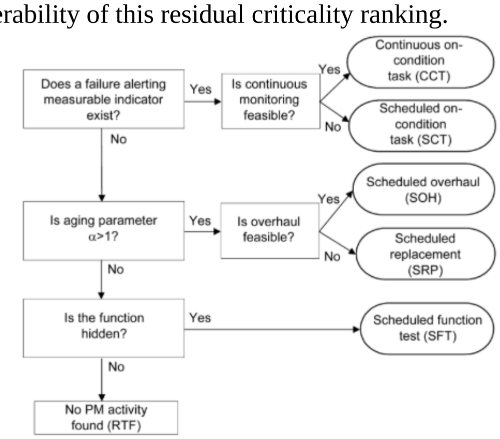


Fig.4 Maintenance task assignment/decision logic [27]

Once the criticality/RPN was determined for all failure modes identified as part of the FMECA, existing operator rounds, and maintenance tasks were mapped to each failure mode, for further analysis as part of the following RCM workshop. The RCM decision logic was applied to each failure mode to determine the optimal maintenance task strategies or operator rounds and routines. In some cases, this was the same as the current strategy when found to be optimal, in other cases, alternately this called for addition or removal/reduction of tasks.

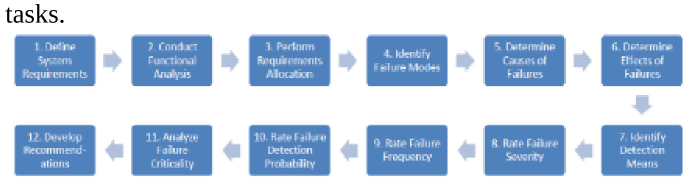


Fig.5 FMECA process [12]

## III. RESULTS

The FMECA identified functions, functional failures, and failure modes. For the key functions, the failure effects, mechanisms, and current controls were identified and an RPN number calculated, with the remainder completed post the workshop. The RCM decision logic has been applied to each failure mode/mechanism, starting with highest RPN item and working down the list. The outcomes of the workshop are reccomendations for the rigid time-based overhaul schedules to be removed, which is a signifacant reduction in maintenance burden, plus significant material & equipment cost savings. Preventive maintenance (e.g. greasing) and predictive maintenance (e.g. condition monitoring) strategies are reccomended to be employed, with major components replaced with ‘rotable’ spares only if required. Major components requiring arm removal can be done on condition, if well maintained these can last 20+ years, where they were previously set at 5 yearly per OEM reccomendations

The safe transfer of liquified natural gas from the LNG storage tanks to LNG ships which are moored at the end of the jetty, is the primary function of the marine loading arms. There is a level of redundancy as there is the ability to continue loading with 3 of 4 arms operational, with relatively minimal disruption and cost, however the slower loading rates can cause some impacts to the shipping schedule, demurrage costs and in the unlikely event that the timing of the slowed down load coencided with full tanks, ‘tank—tops’ could be reached, meaning a total plant shut-down. The mission profile [39] consists of only sporadic movements when extending or retracting the arms to connect or disconnect with an LNG tanker, whilst connected they are subject to only reasonably subtle and small incremental movements as the ship raises or lowers as a result of weight changes or tidal movements. Around 60% of the time, for the remainder of their operational cycle [40], the bearings sit in a dormant mode.

The complete overhaul of the entire arms at no more than 5 yearly intervals as reccomended by the original equipment manufacturer (OEM) is a conservative, costly and undesirable strategy. Following the RCM process has found that the most optimal strategy for the large bearings is to perform more predictive maintenance (PdM) and condition based maintenance (CBM), with sparing strategies to be adjusted in future to ensure spare bearings in stock once their condition begins to degrade, in preparation for eventaul overhaul.

As the other main components, including swivel joints, the powered emergency release coupling (PERC), the double ball valve (DBV), quick-connect-disconnect-coupling (QCDC) and various hydraulic and instrumentation components are all able to be exchanged fairly easily with resources and equipment already on site, causing minimal disruption to shipping, a purely PdM and CBM strategy has been reccomended as the most sensible approach, so the maintenance strategy has been revised and submitted for approval with these changes. Reccomended sparing strategy is to ensure all major and long-lead time components are in stock, keeping rotable complete assembly of swivel joints and overhaul kits, hydraulic cylinders and overhaul kits, and a complete rotable TSA assembly.

The logic for reccomending stocking a complete TSA, is due to the reduced loading of the ships attracting significant cost per load in additional demurrage charges, causing tighter windows between ships, of as little as one day, with potential of hitting ‘tank-tops’ causing a total plant shut-down. When we experience failures, to overhaul the TSA in the workshop and test it could easily span over a couple of shipping windows. Further to this, if we experience a problem with one arm, then further issues with a second arm, this could lead to a total plant shutdown of significant duration, which is a further vulnerability that is not desirable. As the difference in cost of a set of spares, vs. a complete rotable TSA assembly would pay for itself on the first failure, this makes economical sense to keep in stock, along with one set of overhaul spares, thus this is reccomended as part of the sparing strategy for the LNG arms.

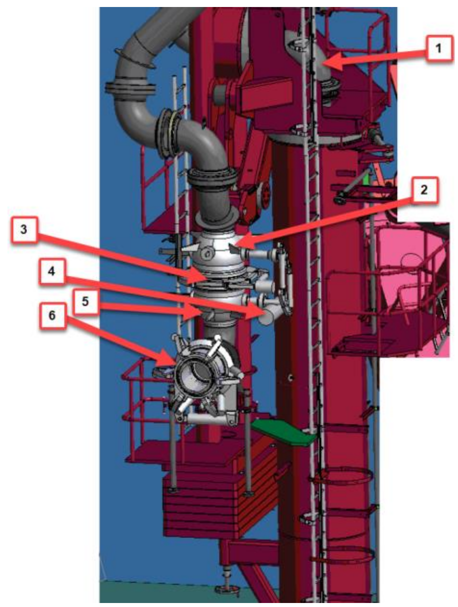

Fig.6 Other main MLA components

TABLE I
COMPONENT LIST FOR MLA (FIG.25)

| NO. | COMPONENT |
|---|---|
| 1 | Upper swivel joint |
| 2 | Upper DBV |
| 3 | PERC |
| 4 | DBV Actuator |
| 5 | Lower DBV |
| 6 | QC/DC |

The 40 year facility plan currently shows a major plant refurbishment activity at around year 20 of the facility being in operation, including complete removal of the arms for a complete overhaul and replacement of all major components, including the large bearings, therefore if they can be maintained well enough to preserve their life well beyond the 20 year milestone, this would also yield a significant cost saving. For this reason, ensuring the bearings are regularly greased to prevent moisture or contaminant ingress is of high importance. The review was also conducted for the LPG/condensate arms, which have much larger windows between ships where maintenance can be performed, these LPG tankers are loaded around once per month. The LPG loading arm system consists of 4x arms, a butane liquid arm, butane vapor return arm, propane liquid arm, and propane vapor return arm. An LPG carrier vessel has a separate tank for butane and another for propane. Loading of liquid butane and propane is ordinarily carried out using both the liquid loading arms and both the vapor return lines. If there is a problem with either of the liquid arms, loading will commence using the good arm, then a crossover piping spool installed from the upstream piping of the failed arm, to the good arm, then product must be fully purged from the line, once achieved the vessel can re-connect, using the re-purposed liquid line, to load the second product. This may take up to three times the normal loading time, costing a couple of days demurrage charges from the shipping company, and depending on the timing of the ship, there could be potential for one of the products hitting 'tank-tops' leading to a total facility shut-down, however this would be unlikely. If there was a problem with an arm that rendered it out of service, loading of LPG carriers would need to continue at this reduced rate, until the failed components of the arm are either repaired or replaced. The activity of removing and re-installing the crossover spool is not desirable, due to the size of the task, involving personnel and cranes working on the jetty, over water, breaking containment of process lines to achieve the task. It is also critical that the butane/propane are not inadvertently mixed on loading due to incomplete purging of the lines, as the rapid boil-off that would be caused in the tank of the vessel could cause an overpressure event. Recommended sparing strategy for the LPG arms is to keep all spares for overhauls of the various components in stock, with rotable spares of the swivel joints, as these are economical to hold from a cost perspective, however unlike the LNG arms, the recommendation is to only hold a complete set of parts for overhaul of a TSA, and not a complete rotable TSA assembly. The logic for this recommendation is that the task of using the crossover spool vs. that of replacing a complete TSA, are equally disruptive to the loading of an LPG vessel, therefore there is no upside from that perspective, also unlike with the LNG arms, there is a window of several weeks between vessels, in which the TSA could be removed, repaired in the workshop, and then reinstalled.

## IV. DISCUSSION AND NEXT STEPS

Prior to the RCM analysis performed on the marine loading arms, there were frequent and costly predetermined scheduled preventive maintenance strategies employed recommended by the OEM (blind acceptance of OEM inputs [6]), predetermined maintenance meaning "preventive maintenance carried out in accordance with established intervals of time or number of units of use but without previous condition investigation" [41]. Outputs from the RCM analysis lead to recommendations for revision of many parts of the maintenance strategy to move to condition based preventive maintenance, "preventive maintenance which include a combination of condition monitoring and/or inspection and/or testing, analysis and the ensuing maintenance actions" [41], based on preventive testing and inspection PT&I, which will maximize availability and minimise cost.

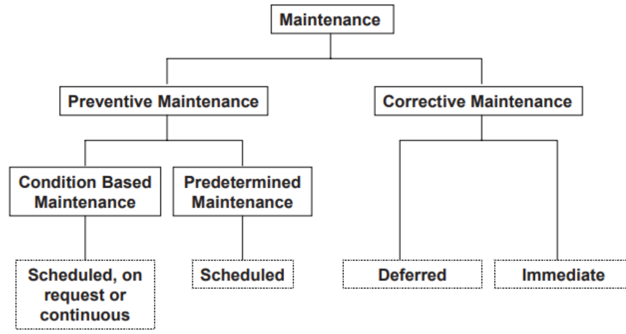

Fig.7 Maintenance - Overall view [41]

As the original maintenance strategy has been built based on a combination of Original Equipment Manufacturer (OEM) generic maintenance recommendations and advice from discipline engineers, prior to having a robust and comprehensive understanding of the site conditions, rather than using RCM based recommendations based on a new understanding of specific site conditions, there are some opportunities to apply this methodology and new knowledge to optimise maintenance strategies. As this is only one area of a large and complex facility, this approach will be used as a blueprint for ongoing maintenance optimization activities and refined as we apply and review the success of the exercise. The rationale or justification of the existing recommendations from discipline engineers and technical authorities is only recorded in brief in the current standards for availability assurance, examples like "frequency of task aligns with OEM requirements", with no documented method for how this decision was reached, along with other similarly 'sketchy' [6] rationales. The application of RCM and its documentation will improve the visibility and understanding of how company engineers have formulated a recommendation for a maintenance strategy, in a routine, logical and auditable way. The RCM process employed in this project should be formally documented and rolled out to the organisation. Once robust FMECA and RCM analysis has been completed on a system or equipment type, this new knowledge can be used to support improvement of maintenance and maintenance support [42], integrated logistic support [43], and maintainability [44] strategies.

Further to the optimisation of maintenance strategy, there are opportunities during the operate and maintain phase, to improve and optimise the maintainability, integrated logistic support, and the maintenance support, as the FMECA and RCM processes that INPEX has recently undertaken, will support the review of these areas. There has been a noticeable positive effect on personnel who participated in the RCM process, which aides to improve morale, buy-in to the maintenance plans, collaboration and knowledge sharing. The notable HRO links to the RCM philosophy are another positive outcome of adopting this process on an ongoing basis, contributing to the organisational preoccupation with failure, deference to expertise, and the attitude of a learning organisation, all key pillars of high reliability organisations. It is strongly recommended to continue to use this process, to continue realizing similar outcomes and continuously improving maintenance strategies, knowledge, and collaboration of personnel across the three key stakeholder departments of Engineering, Maintenance and Production.

## V. CONCLUSION

We can conclude that following the FMECA process, followed by the RCM decision logic, to formulate recommendations for optimal maintenance strategies has proven to be useful, as validated by discipline engineers and technical authorities' concurrence with the approach, and checking with the QRCM decision logic application to give a higher confidence level. There are countless RCM decision logic trees available and in-use with multiple different structures and approaches. No approach is right or wrong, the key is selecting an approach that is simple enough to follow with repeatability, and that ensures a structured thought process is used to determine optimal maintenance strategies that optimise cost and use of resources without creating intolerable safety, environmental, or production risks. By following the RCM process, there is a clear increased morale and engagement of the teams, making positive steps toward becoming a high reliability organisation, with an increase in operational discipline, characterized by the leadership by example, pride in the organisation, capable resources, strong teamwork and employee involvement [45] that comes from adopting this process. In addition to the increased maintenance optimization that comes from the RCM process, there are clear flow on effects as this supports optimal maintenance support and sparing strategy development. RCM should be adopted as a 'living program', conducted periodically over time to continually review and reassess the preventive maintenance decisions that were made in the RCM baselines to ensure continuous improvement toward world class maintenance [6].

## VI. ACKNOWLEDGEMENT

E. Vandenberg greatly appreciates the valuable support of Mark Wilson, Gopinath Chattopadhyay, Andrew Howitt, Hideaki Kaneko, Sakabe Takahashi and the team at INPEX LNG for participation in the series of FMECA and RCM workshops that allowed this work to be completed.

## VII. BIBLIOGRAPHY

[1] SAE International, *SAE-JA1011 - Evaluation Criteria for Reliability Centered Maintenance (RCM) Processes,* Warrendale: SAE International, 2009.

[2] SAE International, *SAE-JA1012 - A Guide to the Reliability-Centered Maintenance (RCM) Standard,* Warrendale: SAE International, 2011.

[3] SAI Global, AS IEC 60300.3.11 - 2011: Dependability management - Application guide - Reliability centred maintenance, Sydney: Standards Australia, 2011.

[4] United States Army, TM 5-698-2 - Technical Manual - Reliability-centered maintenance (RCM) for command, control, communications, computer, intelligence, surveillance, and reconnaissance (C4ISR) facilities, Washington: Headquarters, Department of the Army, 2006.

[5] United States Department of Defense, *MIL-STD-2173(AS) - Reliability-centered maintenance requirements for naval aircraft, weapons systems and support equipment,* Washington: United States Department of Defense, 1981.

[6] A. M. Smith and G. R. Hinchcliffe, RCM - Gateway to World Class Maintenance, Oxford: Elsevier Butterworth-Heinemann, 2004.

[7] International Atomic Energy Agency, *Application of Reliability Centred Maintenance to Optimize Operation and Maintenance in Nuclear Power Plants,* Vienna: International Atomic Energy Agency, 2008.

[8] D. C. Brauer and G. D. Brauer, *Reliability-Centered Maintenance,* vol. 36, IEEE, 1987.

[9] Standards Australia, *AS IEC 60812: Analysis techniques for system reliability—Procedure for failure mode and effects analysis (FMEA),* SAI Global, 2008.

[10] C. S. Carlson, Effective FMEAs - Acheiving Safe, Reliable, and Economical Products and Processes Using Failure Mode and Effects Analysis, New Jersey: Wiley, 2012.

[11] US Department of Defense, MIL-STD-1629A - Procedures for Performing a Failure Mode, Effects and Criticality Analysis, Washington: US Department of Defense, 1980.

[12] D. Gonzalez, Failure Modes and Effects Analysis (FMEA)/Failure Modes, Effects and Criticality Analysis (FMECA), Utica: Quanterion Solutions Incorporated, 2013.

[13] M. Catelani, L. Ciani, L. Cristaldi, M. Faifer, M. Lazzaroni and M. Khalil, "Toward a new definition of FMECA approach," *IEEE Instrumentation and Measurement Society,* 2015.

[14] Standards Australia, *AS IEC 61025-2008 - Fault Tree Analysis,* SAI Global, 2008.

[15] D. Gonzalez, Fault Tree Analysis, Utica: Quanterion Solutions Incorporated, 2013.

[16] United States Nuclear Regulatory Commission, NUREG-0492 - Fault Tree Handbook, Washington: Systems and Reliability Research Office of Nuclear Regulatory Commission, 1981.

[17] International Atomic Energy Agency, *NS-G-2.6 - Maintenance, Sureveillance and In-service Inspection in Nuclear Power Plants,* Vienna: International Atomic Energy Agency, 2002.

[18] R. F. Stapelberg, Handbook of Reliability, Availability, Maintainability and Safety in Engineering Design, London: Springer, 2009.

[19] United States Army, TM 5-698-4 - Technical Manual - Failure modes, effects and criticality analysis (FMECA) for command, control, communications, computer, intelligence, surveillance, and reconnaissance (C4ISR) facilities, Washington: Headquarters, Department of the Army, 2006.

[20] B. S. Dhillon, Applied Reliability and Quality - Fundamentals, Methods and Procedures, London: Springer, 2007.

[21] J. Moubray, *Reliability-Centered Maintenance II*, New York: Industrial Press Inc., 1997.

[22] TechAmerica, *TA-HB-009 - Reliability Program Handbook*, Washington: TechAmerica Standards & Technology Department, 2013.

[23] National Aeronautics and Space Administration, *Reliability-Centered Maintenance Guide for Facilities and Collateral Equipment*, 4th Watch Publishing Co. - US Government, 2008.

[24] B. S. Dhillon, Engineering Maintainability: How To Design For Reliabilty And Easy Maintenance, Houston: Gulf Publishing Company, 1999.

[25] S. Andriulo, M. A. Arleo, F. de Carlo, M. G. Gnomi and M. Tucci, "Effectiveness of maintenance approaches for High Reliability Organisations," in *IFAC Conference Paper Archive*, 2015.

[26] R. Ramanujam and K. H. Roberts, Organizing for Reliability - A Guide for Research and Practice, Calafornia: Stanford University Press, 2018.

[27] K. A. H. Kobbacy and D. N. P. Murthy, Complex System Maintenance Handbook, London: Springer, 2008.

[28] A. M. Smith, Reliability-Centered Maintenance, McGraw-Hill, 1993.

[29] M. Ben-Daya, U. Kumar and D. N. P. Murthy, Introduction to Maintenance Engineering - Modeling, Optimization, and Management, Chichester: Wiley, 2016.

[30] M. Modarres, M. P. Kaminskiy and V. Krivtsov, Reliability Engineering and Risk Analysis - A Practical Guide, 3rd ed., Boca Raton: CRC Press, 2017.

[31] A. K. S. Jardine and A. H. C. Tsang, Maintenance, Replacement and Reliability - Theory and Applications, Boca Raton: CRC Press, 2013.

[32] M. Roush and W. Webb, Applied Reliability Engineering - Volume I, 5th ed., New York: The Center for Reliability Engineering, 2006.

[33] B. W. Niebel, Engineering Maintenance Management, Boca Raton: Taylor and Francis, 1994.

[34] W. Lastinger, "Finding Bearing Failure Through Filter Debris Analysis," *Journal of the Reliability Information Analysis Center*, pp. 8-12, 2006.

[35] E. Calixto, Gas and Oil Reliability Engineering, 2nd ed., Cambridge: Gulf Professional Publishing, 2016.

[36] G. E. Kondhalkar and G. Diwakar, "Crest Factor Measurement by Experimental Vibration Analysis for Preventive Maintenance of Bearings," in *ICRRM 2019 - System Reliability, Quality Control, Safety, Maintenance and Management - Applications to Civil, Mechanical and Chemical Engineering*, Singapore, 2019.

[37] S. Mannan, Lees' Loss Prevention in the Process Industries - Hazard identification, assessment and control, Oxford: Elsevier Butterworth-Heinemann, 2012.

[38] D. J. Smith, Reliability Maintainability and Risk: Practical Methods for Engineers, 8th ed., Oxford: Butterworth-Heinemann, 2011.

[39] International Electrotechnical Commission, *IEC TR 62380: Reliability data handbook*, Geneva: International Electrotechnical Commission, 2004.

[40] United States Department of Defense, *MIL-STD-756B: Reliability Modeling and Prediction*, Washington DC: Department of Defense, 1981.

[41] British Standards Institute / European Committee for Standardisation, *BS EN 13306:2010 - Maintenance - Maintenance terminology*, Brussels: British Standards Institute / European Committee for Standardisation, 2010.

[42] SAI Global, *AS IEC 60300.3.14 - Dependability management - Application guide - Maintenance and maintenance support*, Sydney: Standards Australia, 2016.

[43] SAI Global, *AS IEC 60300.3.12 - Dependability Management - Application Guide - Integrated Logistic Support*, Sydney: Standards Australia, 2011.

[44] SAI Global, *AS IEC 60300.3.10 - Dependability Management - Application Guide - Maintainability*, Sydney: Standards Australia, 2004.

[45] A. Hopkins, Learning from High Reliability Organisations, Wolters Kluwer, CCH, 2013.

[46] E. Carlucci and L. Tognarelli, "Mixed Weibull distribution as best representative of forced outage distribution to be implemented in BlockSim," *Safety and Reliability of Complex Engineered Systems*, pp. 2169-2176, 2015.

[47] A. Feinberg, Thermodynamic Degradation Science - Physics of Failure, Accelerated Testing, Fatigue, and Reliability Applications, Chichester: Wiley, 2016.

[48] E. Zabawski, "Failure probability curves: A common belief is not entirely true," *Tribology and Lubrication Technology*, vol. 74, no. 2, p. 8, 2018.

[49] P. O'Connor and A. Kleyner, Practical Reliability Engineering, 5th ed., Sussex: Wiley, 2012.

[50] Brevini, "Leonessa Slew Bearings," 2019. [Online]. Available: http://www.brevinipowertransmission.com/wp-content/uploads/2019/02/CatalogoLEONESSAbrevini-GB-2012.pdf. [Accessed 2019].

[51] M. Basson, RCM3™: Risk-Based Reliability Centered Maintenance, Connecticut: Industrial Press, Inc., 2018.

[52] Quanterion Solutions Incorporated, System Reliability Toolkit - V: New Approaches and Practical Applications, New York: Quanterion Solutions Incorporated, 2015.